Low Speed Pressure Sensitive Paint Measurements-
Requirements and Applications

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ABSTRACT

The utility of pressure sensitive paint (PSP) and temperature sensitive paint (TSP) technology in determining surface-pressure and temperature distributions for aerodynamic applications has been demonstrated. While most of these applications have been at mid-subsonic (typically > Mach 0.3) to hypersonic speed regimes, several aerodynamic and automotive applications have been conducted at lower speeds. Obtaining global pressure measurements using PSP at low speeds is made difficult because of several factors. First, the measurements are generally made in a pressure region where the sensitivity of the paint is at its lowest. Second, the small overall changes in pressure can be difficult to resolve. Third, the temperature sensitivity of the PSP can cause relatively large errors in the measured pressure if even a small change in the surface temperature is experienced. Different paint formulations, instrumentation, data acquisition, and data analysis techniques have been actively pursued to help overcome these problems. In this paper, we will describe some of these advancements and show some recent work that has been done implementing these improvements in low speed wind tunnels

INTRODUCTION

The accurate determination of spatially continuous pressure and temperature distributions on aerodynamic surfaces is critical for the understanding of complex flow mechanisms and for comparison with computational fluid dynamics (CFD) predictions. Conventional pressure measurements are based on pressure taps and electronically scanned pressure transducers. While these approaches provide accurate pressure information, pressure taps are limited to providing data at discrete points. Moreover, the integration of a sufficient number of pressure taps on a surface can be time and labor intensive and expensive.

The ability to make an accurate determination of pressure and temperature distributions over an aerodynamic surface based on an emitted optical signal from a luminescent coating has recently been developed.[1-12] Pressure sensitive paint (PSP) measurements exploit the oxygen (O_2) sensitivity of luminescent probe molecules suspended in gas-permeable binder materials. If the test surface under study is immersed in an atmosphere containing O_2 (e.g. air), the recovered luminescence intensity can be described by the Stern-Volmer relationship[13]

$$\frac{I_0}{I} = 1 + K_{SV} P_{O_2}$$

where I_0 is the luminescence intensity in the absence of O_2 (i.e. vacuum), I is the luminescence intensity at some partial pressure of oxygen P_{O2}, and K_{SV} is the Stern-Volmer constant.

Since it is a practical impossibility to measure I_0 in a wind tunnel application, a modified form of the Stern-Volmer equation is typically used. This form replaces the vacuum calibration (I_0) with a reference standard

$$\frac{I_{REF}}{I} = A(T) + B(T)\frac{P}{P_{REF}}$$

where I_{REF} is the recovered luminescence intensity at a reference pressure, P_{REF}. This reference pressure is typically the static tunnel pressure when no wind is applied. Thus I_{REF} is referred to as the "wind-off" intensity. I is the recovered luminescence intensity at some pressure P. Since this data is collected at a specific condition in the wind tunnel, I is also referred to as the "wind-on" intensity. A and B are temperature dependent constants for a given PSP formulation and are usually determined before hand using laboratory calibration procedures.

Most PSP applications have been conducted at speeds ranging from mid-subsonic (typically > Mach 0.3) to transonic to supersonic and beyond. Obtaining accurate pressure distributions at these speed ranges is made easier because of the greater overall change in pressure experienced at the surface (typically ≥ ~ 2 psi) and/or the lower operating pressure of the wind tunnel. However, several low speed aerodynamic and automotive test surfaces have been interrogated recently using PSP.[9,14] This work will briefly describe some of the requirements needed of a PSP and instrumentally for low speed applications. Two low speed tests carried out at the NASA Langley Research Center will also be described.

Low speed PSP Measurements

The application of PSP technology to low speed flow applications is contingent on significant improvements in sensitivity at near-ambient pressure (14.7 ± 2 psia). The salient criteria governing the sensitivity of the PSP include the probe luminescence lifetime (τ), quantum efficiency (φ_e), and accessibility to O_2. Lifetime and quantum efficiency characteristics of a PSP are dominated by the photophysics of the luminescent species. Probe accessibility to O_2 determines the efficiency of the quenching process, and is modulated by the porosity or void volume of the binder support matrix. A typical PSP response to pressure is shown in Figure 1.

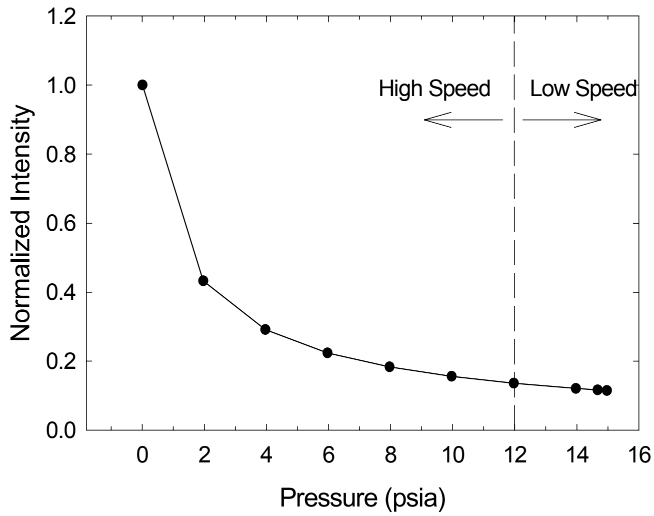

Figure 1. Typical recovered luminescence intensity from a PSP as a function of pressure.

From these data it is readily apparent that in the low speed regime, response of the PSP to slight changes in pressure is extremely small. Because of the overall small changes in pressure experienced in the low speed regime (typically < 0.5 psi and possibly much lower depending on aerodynamic shape), instrumental factors can become significant sources of error in determining accurate pressure distributions. Another mitigating factor in the recovery of global pressure distributions in the low speed regime is the inherent temperature sensitivity of the PSP. A typical temperature sensitivity plot of a PSP at vacuum and at ambient pressure is shown in Figure 2.

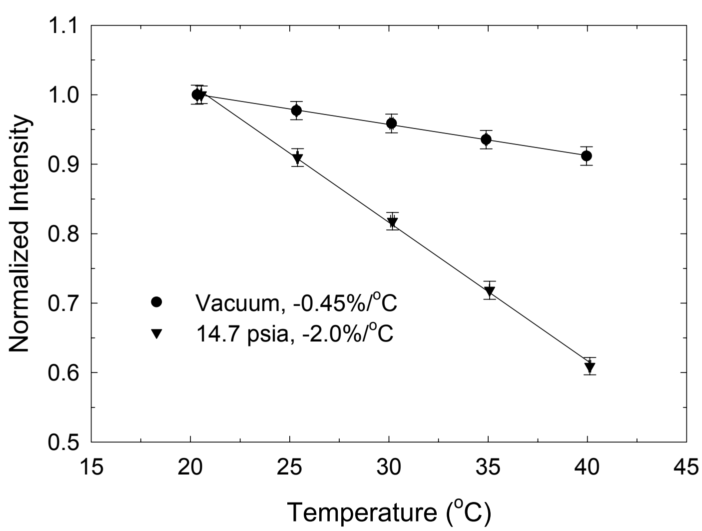

Figure 2. Typical temperature response of a PSP at vacuum and at ambient pressure (14.7 psia).

These data show that the temperature response of the PSP arises from two different phenomena.[15] First there is the inherent temperature dependence of the luminescent output from the probe itself. This is manifest as the temperature sensitivity at vacuum. The second source of temperature sensitivity is the temperature dependence of the solubility and diffusion of O_2 in the binder itself. A considerable amount of research has been devoted to dealing with the problem of the temperature sensitivity of PSP. Several strategies have been implemented with varying degrees of success, including 1) *in situ* calibration methods, which correlate the PSP luminescence response with existing pressure taps on the surface, 2) concurrent temperature measurements using temperature sensitive paint (TSP) or thermocouples, and 3) multi-luminophore paint formulations that provide unique pressure and temperature signals. For nearly all temperature compensation methods, errors due to uncompensated PSP temperature sensitivity and/or the compensation method itself is the main source of error in determining accurate pressure distributions.

Instrument Factors

A typical instrument for measuring global pressure distributions using PSP has two main pieces: excitation source(s) and detector(s). Each device can have its own sources of noise and will be looked at in more detail. For this work, all consideration will be limited to the more commonly used steady-state intensity measurement technique, although it should be realized that several lifetime-based imaging techniques are being developed and have recently been used in wind tunnel applications.

Excitation Source(s): Because of the small pressure changes observed in most low speed PSP tests, stability of the excitation source becomes critical. Most PSP applications in wind tunnels have used lasers, UV lamps, or newly available solid-state LED lamps as excitation sources. The advantages and disadvantages of each type are described below.

Lasers: Typically the third harmonic of a pulsed Nd:YAG laser (355 nm) or a continuous-wave argon ion laser are the type of laser used in PSP measurements. The advantage of a laser lies in its high intensity output. However, this advantage can be greatly offset by its disadvantages. First, there are added safety and operational procedures that must be adhered to, not only for personnel but also for the facility. Second, a laser can be much more costly than a lamp, thus mitigating the number that can typically be used. Third, a laser generally requires stringent power and cooling requirements that a wind tunnel facility must have installed for proper operation. Finally, for low speed tests, stability can be an issue, with instabilities of pulsed lasers being as high a 1% variation pulse-to-pulse. These variations can be improved using complicated data acquisition and setup procedures. Because of these disadvantages, lasers were not considered for the low speed PSP applications.

UV Lamps: The standard UV lamp is generally a xenon or tungsten-halogen lamp with added filtering to block the undesired wavelengths from the broadband source. Because of the extensive filtering required, excess energy is converted to heat, which must be dissipated. This is usually accomplished by externally cooling the unit. Without adequate cooling, instabilities can appear in both the power supply and the bulb of the lamp. The advantage to using one of these broadband sources is that, if sufficient filtering is applied, UV lamps offer a relatively large amount of power from 370 to 400 nm, the excitation maximum for platinum meso-tetra(pentafluorophenyl) porphine [Pt(TfPP)]-based PSPs.

LEDs: Solid-state blue light emitting diode (LED)-based lamps have recently been introduced as excitation sources for PSP measurements.[16] These lamps exhibit the excellent stability required to measure the small pressure changes observed in low speed applications. Secondly, as very little energy is converted to heat, external cooling requirements are minimal. However, current ultra-bright blue LEDs emit a relatively narrow band of light (~20 nm FWHM) centered at about 470 nm. In this range, the absorbance of the Pt(TfPP) is only about 20% of its maximum value. Also, the output of the LEDs is the lowest of the three sources discussed. Still, their small size, low cost, and ease of operation make using many lamps feasible for most wind tunnel facilities.

Stability: Because of the importance of lamp stability for low speed applications, the stability of a UV lamp and a blue LED was investigated. This was accomplished by illuminating a bare aluminum surface with the lamp in question, and measuring the reflected light over time with a silicon photodiode. The results are shown in Figure 3.

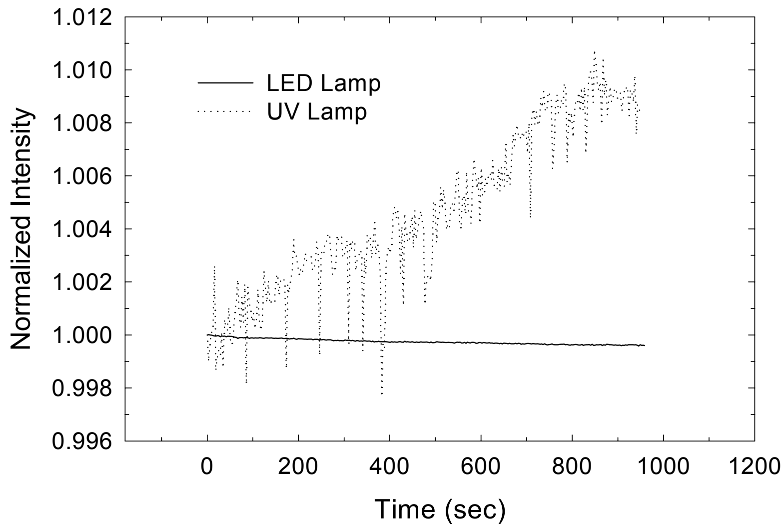

Figure 3. Stability of a blue LED lamp and a UV lamp over time. Both lamps have had 1 hour of warm-up time.

These data were collected approximately one hour after the lamps had been turned on in order to minimize drift associated with the warm-up of the electronics. The stability of the blue LED lamp (~0.01%) is about 30 times that of the UV lamp (~0.30%).

Detectors: An imaging system containing sufficient digital resolution must be used to adequately resolve the small changes in the intensity of the PSP at high static pressure and small changes in pressure over a wind tunnel model. CCD cameras are typically used for PSP imaging applications due to their high spatial resolution (> one million pixels) and relative low cost. However, one problem with using a digital camera is the presence of dark current, which can be a significant source of error where low light levels are expected. To decrease the amount of dark current present in the system, all experiments were performed using back-illuminated slow-scan scientific grade CCDs.

To further resolve the small changes in recovered luminescence, the camera must have sufficient digital resolution. Table 1 shows the change in the number of integrated counts from a CCD that one can expect from a 2 psi change in pressure (~10% change in intensity for a typical PSP) and the change in integrated counts if one wants to resolve one one-hundredth of the pressure (~0.1% change in intensity).

Digital Resolution	Number of Gray Levels	2 psi Change	1% Resolution
8-bit	256	12.5	0.125
12-bit	4096	204.8	2.05
14-bit	16,384	819.2	8.19
16-bit	65,536	3276.8	32.8

Table 1. Estimated change in the integrated counts for cameras of various digital resolutions for a 2-psi change in pressure and a required resolution of 1%. These values assume that the camera is operated such that half the electronic well is filled to insure that the linearity of the CCD is maintained.

This table shows that to achieve adequate resolution at this moderate pressure change (typical of an atmospheric indraft wind tunnel running at Mach 0.5), the more digital resolution the camera has, the better. However, with an increase in digital resolution, there is an increase in the camera costs.

Paint Formulations

Two paint formulations were investigated for use as in low speed PSP applications. The first PSP was based on a formulation developed at NASA Langley Research Center and has been described previously.[17] This formulation uses a two-layer approach: a white basecoat is applied to a clean model surface followed by a layer containing Pt(TfPP) immobilized in a polymer matrix. The basecoat served to mask any imperfections in the model surface and also acts as an adhesive for the PSP layer. This formulation was chosen because it has seen extensive previous use in wind tunnel applications.

The second formulation involves the use of thermochromic dyes that change color with temperature. The dyes were chosen so that as the temperature increases, the dyes become transparent, resulting in a greater reflectivity of the Pt(TfPP) luminescence. The concentration of the dyes added to the PSP was adjusted such that the change in reflectivity cancels out the decrease in luminescence from the Pt(TfPP) due to temperature. These thermochromic dyes were sequestered in the white basecoat layer. Details of this temperature insensitive PSP (TI PSP) are to be published shortly.

Low Speed Wind Tunnel Applications

Two low speed wind tunnel tests were recently conducted at facilities at the NASA Langley Research Center. The first test involved a reverse ramp model and was conducted at the 15-inch Low-Turbulence Wind Tunnel (LTT). The second test was conducted at the Subsonic Aerodynamic Research Tunnel (SBRT) on a hypersonic fighter model designed and constructed by students in the Joint Institute for Advancement of Flight Sciences program.

LTT Test: The purpose of this test was to determine the minimum pressure resolution that can be measured using PSP in a low speed application. In order to accomplish this, a reverse ramp model was painted with the two-layer formulation described previously. Because of the small pressure change expected across the surface of the model, ultra-stable ultra-bright green LED-based lamps were used for illumination. These lamps produce spectrally narrow (~30 nm) light centered at 520 nm. The Pt(TfPP) absorbance at this wavelength is approximately 60% maximum. Recovered luminescence was imaged using a 14-bit back-illuminated scientific-grade CCD camera. A photograph of the set-up is shown in Figure 4.

Figure 4. Photograph depicting PSP painted reverse ramp model and data acquisition set-up.

Illumination and image acquisition were accomplished by mounting the respective components above the tunnel and imaging through the glass plate that was the top of the test section. Data acquisition consisted of acquiring and averaging 100 "wind-off" images followed by 100 "wind-on" images while the tunnel was running at 127 ft/sec (~87 mph). Registration of the "wind-on" images to the "wind-off" images was done using a cross-correlate and compare algorithm described previously.[18]

Because of the presence of several pressure taps (27) in the model that were visible in the PSP images, *in situ* calibration was used to account for any temperature change on the model surface at run condition. This was done by correlating the PSP response close to each pressure tap. An *in situ* calibrated image along with a correlation between the PSP response and the pressures measured at the pressure taps is shown in Figure 5.

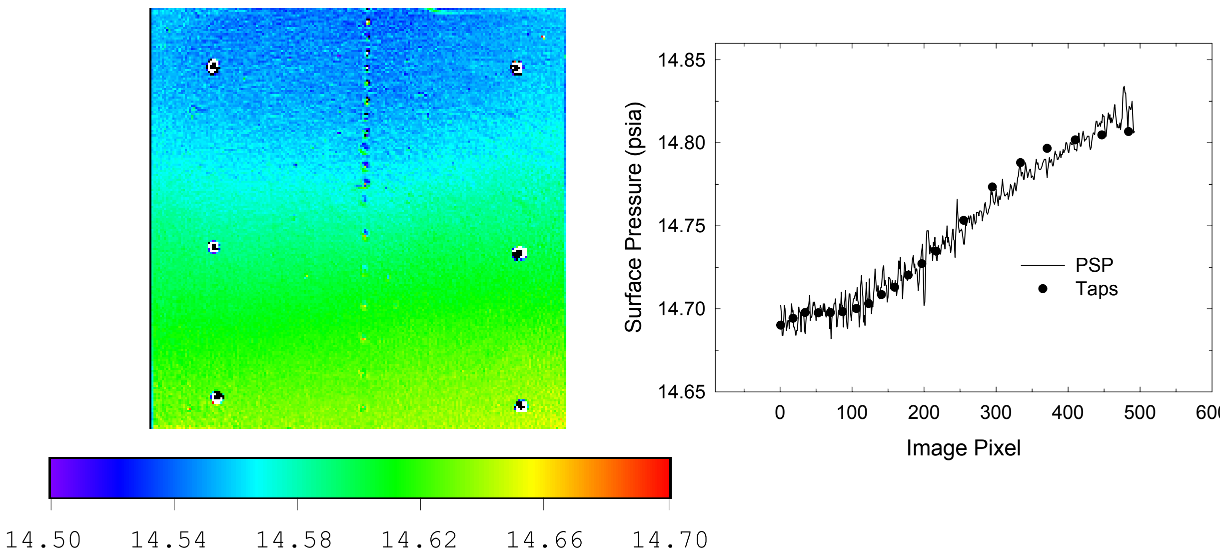

Figure 5. *In situ* calibrated PSP image and correlation with pressure tap data for the reverse ramp model in an airflow of 172 ft/sec (~87 mph). Scale is in psia.

From the graph of the correlation between the PSP and pressure tap responses; it is evident that with sufficient instrumentation and data acquisition techniques one can easily resolve sub-0.1 psi pressure changes (~0.02 psi).

SBRT Test: The purpose of this test was to evaluate the performance of the TI PSP for use in low speed applications. The tested model contained complex geometries resulting in localized temperature variations across the surface. Illumination and image acquisition was accomplished using three UV lamps and a 16-bit back-illuminated scientific-grade CCD camera. A photo of the painted model is shown in Figure 6.

Figure 6. Hypersonic fighter model painted with TI PSP.

As in the previous test, all illumination and data acquisition was accomplished by mounting the respective components above the tunnel and imaging through the glass plate that was the top of the test section. For each test point, the tunnel air speed was set to 170 fps (~87 mph). Several different angles of attack for both the top and bottom of the model were imaged. Because of the lack of pressure taps in the model, *in situ* calibration could not be used to correct any temperature variations. An *a priori* calibration of the TI PSP was performed using a calibration chamber, a UV lamp, and the 16-bit CCD camera. This calibration was then applied to registered and ratioed PSP images. A typical result of both the top and bottom of the model at 0 deg angle of attack is shown in Figure 7.

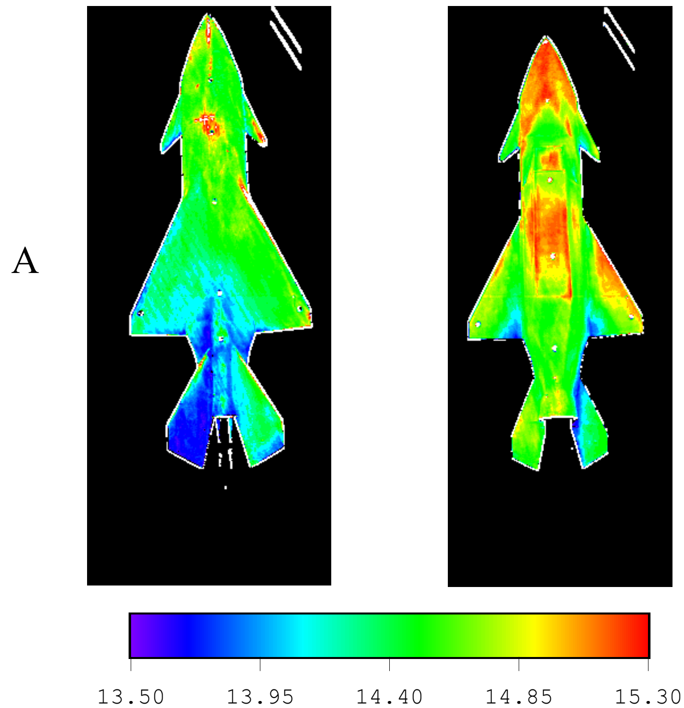

Figure 7. PSP images of the top (A) and bottom (B) of the hypersonic fighter model at 0 deg angle of attack and air speed of 170 fps (~87 mph). Scale is in psia.

These images show several interesting flow phenomena around the nose of the fighter and the inlet. Without pressure taps in the model, it is impossible to determine if temperature correction was complete, however, the relatively large pressure changes calculated using the *a priori* calibration determined in the lab seem to indicate that some of the temperature was not corrected. The TI PSP is currently being optimized and should find use as a low speed PSP.

Conclusions

In order to accurately determine global pressure distributions at low speed using PSP, care must be taken to insure that measurement errors are minimized. To minimize the errors resulting from the illumination source, ultra-stable LEDs or UV lamps should be used. Adequate cooling of the illumination source should also be considered, as small changes in the operating temperature of the source could manifest as large errors in the PSP measurements. Also, a CCD camera of sufficient digital resolution must also be used to resolve the small changes in pressure experienced in these measurements. Two low speed applications have been described and have shown that PSP can determine pressure changes as small as 0.02 psi.

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